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System-Level Lifetime-Oriented Power Sharing Control of Paralleled DC/DC Converters

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***Abstract*— Thermal cycling is a critical stressor on semiconductor elements as they are the main functional components of power electronic converters. Load variation of a converter causes temperature swing, which intensively affects the lifetime of semiconductor switches. In this paper, an active thermal controlling method is proposed in order to enhance the overall system reliability. The proposed strategy applies power sharing among the converters by taking into account the lifetime of the power switches in the paralleled converters under different loading conditions. Hence, the lifetime of the converters is equally consumed in terms of load variations, and the overall system reliability is improved. Simulations and experimental case studies on two parallel-connected power converters have demonstrated that the power sharing control is an effective solution in terms of enhancing the overall power system reliability.**

Keywords—lifetime; reliability; dc power system; power sharing; system-level reliability

I. INTRODUCTION

The global shift of energy paradigm to carbon-free technologies has intensified the role of power electronics technology in power conversion process and accordingly in power systems. Moving towards to the Power Electronic based Power Systems (PEPSs) [1], however, also pose new challenges to the reliable operation of the power system. Thereby, Design for Reliability (DfR) in power electronic converters has gained significant interest recently [2]–[9]. Furthermore, system-level reliability assessment during operation of a converter as the main part of a PEPS should be considered in order to manage the system risks.

Power semiconductor devices not only serve as the main functional element in a power converter but also they are the most fragile components [10]–[12] in a power electronics system. Therefore, their lifetime significantly affects the whole reliability of the system. The main cause of a failure of a component can be related to the disagreement of the stress and strength levels. For the power electronics converters, the stress is loading condition or thermal cycling and the strength is an inherent ability of the converters' components to tolerate thermal cycles. This ability of the system during an expected period is known as reliability.

Based on the physics-of-failure reliability analysis, as power electronics devices are exposed to periodic thermo-mechanical stress, thermal cycling is identified as one of the major critical stressors [13]–[17]. Following the developed empirical models [13], [15], lifetime of power semiconductor devices is closely related to the peak-to-peak variation of their junction temperature (i.e., ΔT_j). Hence, any attempt at reducing the junction temperature swing can increase the number of the cycles to failure and thereby increase the lifetime.

One of the approaches in improving lifetime and reliability of power semiconductors is known as active thermal control for reliability [8], [14]. For instance in [3], [7] different modulation strategies have been introduced in order to reduce the thermal loss of converters. Furthermore, reactive power control under grid code requirements is presented in [4] in order to improve the thermal cycling of a wind turbine. Thermal stress reduction employing active power is further presented in [5], [6] by utilizing a storage system in the dc link of a back-to-back based wind converter. Lifetime extension employing active thermal control is introduced in [8] by adapting the switching frequency, while the system efficiency is reduced. Optimal operation of parallel converters is presented in [9] extending the lifetime while increasing the thermal stress of the components.

An effective technique to reduce the stress in a power converter, and hence increase the system reliability, is to reduce the thermal cycling either by decreasing the temperature swing or by reducing the mean temperature value. Thermal cycling of a converter is a result of different disturbances with various time constants including climate change, device switching, control, and loading [11]. Modification of converter loading can easily be performed by changing the operation point of the converter, hence the thermal cycling can actively be controlled and the overall reliability of the system can be enhanced.

Active thermal control of paralleled converters in PEPS can be carried out by employing suitable power sharing approaches. So far, power management and load sharing approaches have been presented employing voltage droop method [18], [19] and frequency droop control [20], [21], where the load sharing among paralleled converters has been performed proportional to the corresponding rated powers. Furthermore, reference [22] presents another droop approach taking into account the power loss of converters and hence improving the overall system efficiency. A cost-based droop approach is also introduced in [23] for power sharing control by considering the operational cost of power sources. However, reliability and lifetime of power converters have not been taken into consideration in the literature.

In this paper, the impact of loading profile in paralleled converters in a dc PEPS on the thermal stress of switching power semiconductors is investigated, and a new power sharing strategy is proposed in order to achieve better thermal loading and improve the overall system lifetime and reliability. In the following, Section II describes the system-level reliability assessment in PEPSs and introduces the proposed reliability index employed in this paper. The proposed system-level lifetime extension approach by active thermal management is explained in Section III. Furthermore, simulations and experimental results are reported in Section IV and Section V validating the effectiveness of the proposed scheme. Finally, the outcomes are summarized in Section VI.

II. SYSTEM-LEVEL RELIABILITY ASSESSMENT

A typical PEPS is shown in Fig. 1(a) including *N* converters (three/single phase) connected to the utility grid and distributed loads of the system. Following the PEPS design strategies and reliability criteria – i.e., standby backup system, redundant system, (n-1) reliability criterion, etc. – the overall reliability of the PEPS $\mathcal{R}_{system}$ can be measured by the reliability of the converters $\mathcal{R}_c$. Meanwhile, the reliability of a power converter can be classified as software and hardware reliability. The software reliability deals with the control and protection programming in which so far a liitle efforts have been performed, while it is of high importance. However, much research have been carried out in terms of hardware reliability assessment including failure analysis of semiconductor switches, capacitors, gate drives and etc.

The reliability (or unreliability) of a converter can be found by combining the reliability of each components working in parallel or series together as seen in Fig. 1(b) in order to carry out a predefined duty. From the reliability engineering, for instance, if the expected operation of a system with two components depends on operating of both components, thus the reliability of the system is defined as:

$$\mathcal{R}_{system} = \mathcal{R}_1 \cdot \mathcal{R}_2 \,, \tag{1}$$

where $\mathcal{R}_i$ is the reliability of the i^{th} component. Hence, the system succeeds if and only if every individual component succeeds, and consequently, the system will be as weak as the weakest component. For example, the reliability model of a gate-drive and switch is a series system, since the failure of one of them causes the system to fail. Furthermore, if the reliability of the system depends on operating of at least one of the components, then the system reliability can be found as:

$$\mathcal{R}_{system} = 1-(1-\mathcal{R}_1)\cdot(1-\mathcal{R}_2)\,, \tag{2}$$

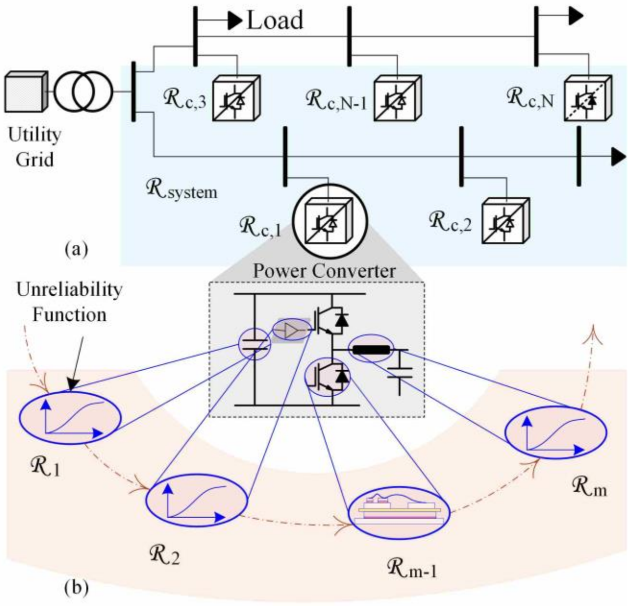


Fig. 1. Reliability assessment from component-level to system-level. (a) Typical Power Electronic based Power System, and (b) relation between reliability of a converter and corresponding components – $\mathcal{R}_i$ = Reliability of i^{th} component of a converter, $\mathcal{R}_{c,k}$ = Reliability of k^{th} converter.

and the reliability model of system is parallel connection of the components. In parallel systems, the reliability of the system is higher than the reliability of any individual component. The reliability of a converter can be calculated by combining the reliability of different components including power switches, gate drives, capacitors, inductors, control system, etc., which can be modeled as series or parallel systems. After defining the converter reliability, the overall PEPS reliability can be found by combining the reliability of the converters considering the designing strategy.

In this paper, lifetime is considered as the reliability index in a simplified dc PEPS with two boost converter. At the component level, the lifetime of the semiconductor switch is considered as an approximation of converter lifetime, since the power semiconductor devices are the most vulnerable components of power converters due to high dissipation density and intense thermal cycling [10]–[12]. From the system-level point of view, the lifetime of the overall system depends on a converter with the lowest lifetime and hence the reliability model of the system should be a series connection of the lifetime of both converters. Hence, the purpose of this paper is to improve the overall system lifetime (as the reliability index) by real-time measuring the Consumed Lifetime (CL) of the converters, and equally sharing the CL between the converters. The proposed control system is explained in the following Section.

III. PROPOSED DROOP APPROACH

A load sharing approach among converters is presented considering a simple load profile (two-step load with light and heavy loading levels) to actively control the thermal cycling and hence improve the overall system lifetime. In the proposed

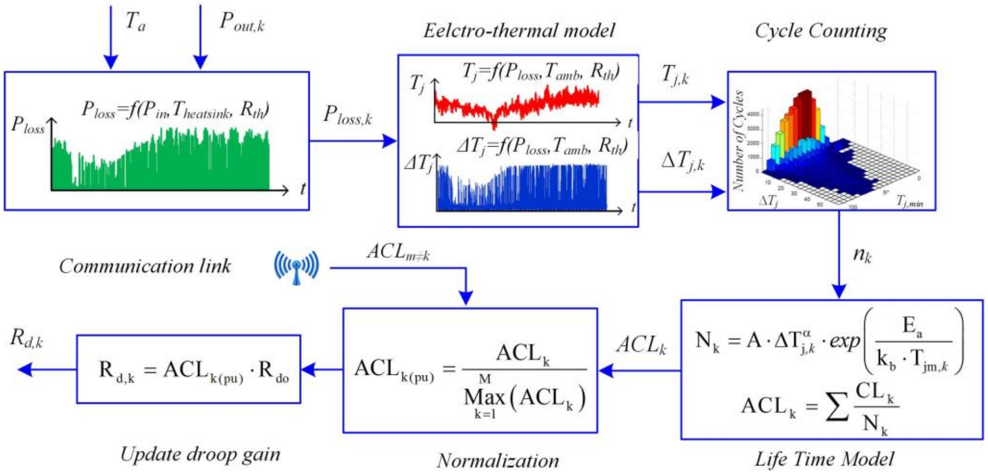


Fig. 2. Proposed lifetime-oriented droop gain adjustment for k^{th} converter in a power electronic based power system.

approach, the CL of converters is taken into account in which all the converters have the same lifetime consumption due to the load variation. In order to control the mentioned thermal stress of the converters, the conventional droop method [20] are employed where the droop gains are adjusted by the CL of the converters.

The proposed lifetime-oriented load sharing approach is shown in Fig. 3, where the droop gains ($R_{d,k}$) will be updated according to the CL of the converters. The power loss on the semiconductor devices can be calculated based on the operating point of the converter (P_{out}), heatsink temperature and corresponding thermal impedance. The junction temperature (T_j) and temperature swing (ΔT_j) can be calculated using the power loss and ambient temperature applied to the electro-thermal model of the converter [12]. Meanwhile, rain-flow counting method can be employed to calculate the thermal cycles (n_k) of the k^{th} converter. The CL of the converter can be calculated as CL = n_k/N_k where N_k is the number of cycles to failure following (3) [24], E_a and k_b are the activation energy and Boltzmann constant, α and A are obtained from LESIT project. Furthermore, N_k must be normalized for different thermal cycles' period (t_{on}) following (4) [17].

$$N_k = A \cdot \Delta T_{j,k}^{\alpha} \cdot exp\left(\frac{E_a}{k_b \cdot T_{jm,k}}\right). \tag{3}$$

$$\frac{N_k(t_{on})}{N_k(1.5s)} = \left(\frac{t_{on}}{1.5s}\right)^{-0.3}, \quad 0.1s \le t_{on} \le 60s \tag{4}$$

In order to consider the whole fatigue of the converter during an operating period, the effect of each thermal cycle on the CL must be accumulated from the initial point to the present. Hence, the Accumulated Consumed Lifetime of the k^{th} converter (ACL_k) can be calculated as:

$$ACL_k = \sum \frac{CL_k}{N_k} . \tag{5}$$

The per-unit ACL of the k^{th} converter is defined as:

$$ACL_{k(pu)} = \frac{ACL_k}{\underset{k=1}{\overset{M}{Max}}(ACL_k)}, \tag{6}$$

where M is the number of converters. If the ACL of one converter is smaller than the other one, the corresponding droop gain should be chosen smaller in order to supply more power and thus consume more lifetime. A simple approach to adjust the droop gains is given in (7), where R_{do} is the maximum allowable droop gain.

$$R_{d,k} = ACL_{k(pu)} \cdot R_{do} \tag{7}$$

Following the ACL of each converter, the corresponding droop gains ($R_{d,k}$) need to be updated to reach the same ACL for all converters. As a result, in this approach, the load sharing among the converters are performed based on thermal stress on the semiconductor switches, hence by actively controlling the loading of converters, the ACL of converters can be equalized and the overall system reliability can be enhanced. In order to evaluate the effectiveness of the proposed approach, simulation and experimental tests are presented in the following.

IV. SIMULATION RESULTS

In this section, two boost converters are considered operating in parallel to support a common load as shown in Fig. 3. The converter parameters are given in Table I. Simulation results are given in Fig. 4 implying the effectiveness of the proposed droop approach. A repeated two level load (including 2.5 kW and 5 kW each one for 2 sec) is supplied by the converters. Power sharing between the two converters employing the conventional droop controller is shown in Fig. 4(a). Furthermore, the junction temperature of the corresponding switches is given in Fig. 4(c), where the junction temperature swing in the conventional approach is 51ºC and 44ºC respectively for the first and second converters. Hence, the first converter has more thermal stress than the second one. Applying the proposed approach, the first converter supplies more power than the second one as shown in Fig. 4(b) implying reducing the thermal stress of the first

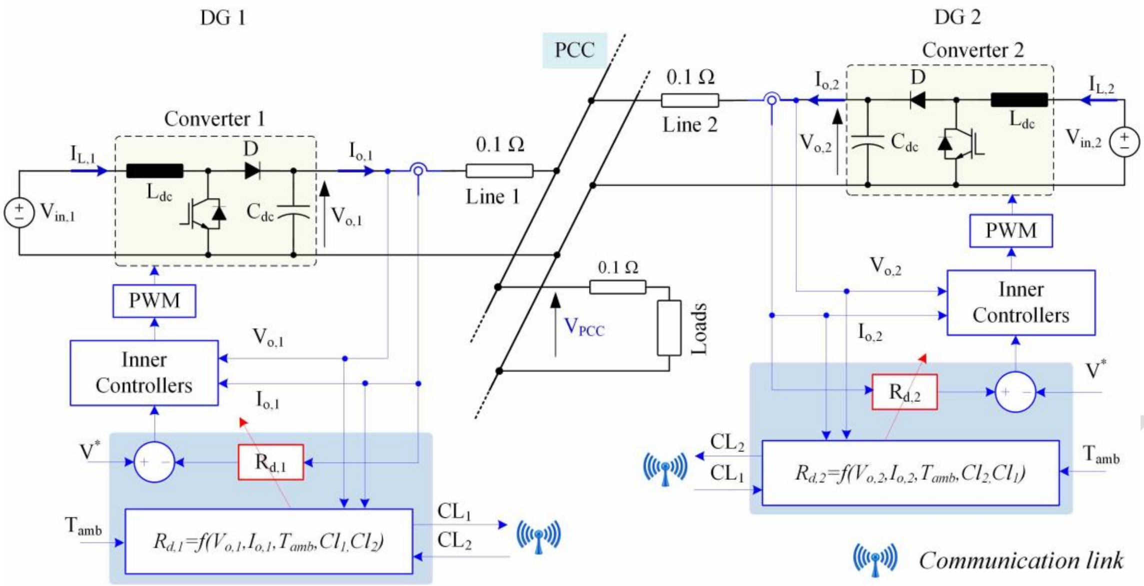


Fig. 3. Schematic of the implemented dc grid having two boost converters with inner controllers (current and voltage regulators).

TABLE I. Parameters of the Implemented DC Grid

Parameter / Symbol	**Value**	
	Converter 1 (DG 1)	**Converter 2 (DG 2)**
L_{dc} (mH)	1.8	3.6
C_{dc} (μF)	500	500
Switching Frequency (kHz)	20	10
Current Regulator (k_{pi}+k_{ii}/s)	0.05+2/s	0.05+2/s
Voltage Regulator (k_{pv}+k_{pi}/s)	0.45+20/s	0.45+20/s

converter. As shown in Fig. 4(c), the temperature swing of the first converter is decreased where the temperature swing of the second one is increased. Hence, the temperature swing has the same value of 47ºC. Therefore, the thermal cycling is actively controlled in order to equally share the CL between the converters.

V. EXPERIMENTAL VALIDATIONS

A photograph of the implemented dc grid with the boost-converter structure is shown in Fig. 5. For the experiments, the applied load profile has two repeated levels including 2.5 kW for 5 minutes and 5 kW for 5 minutes. In the following tests, the effect of loading of the converters on the temperature swing, which affects the lifetime of the converters is demonstrated.

Putting the droop coefficients for the converters equal to R_{d1} = 1.5 and R_{d2} = 0.9, the output currents of converters are shown in Fig. 6(a) for two light and heavy loading conditions of the grid. The temperature of the converters' heatsink is also shown in Fig. 6(b & c), where the temperature variation of heatsinks are Δt_1 = 15.2ºC and Δt_2 = 10.9ºC. Therefore, considering the mentioned droop gains makes the first converter enduring more stress (i.e., temperature cycling) than the first one.

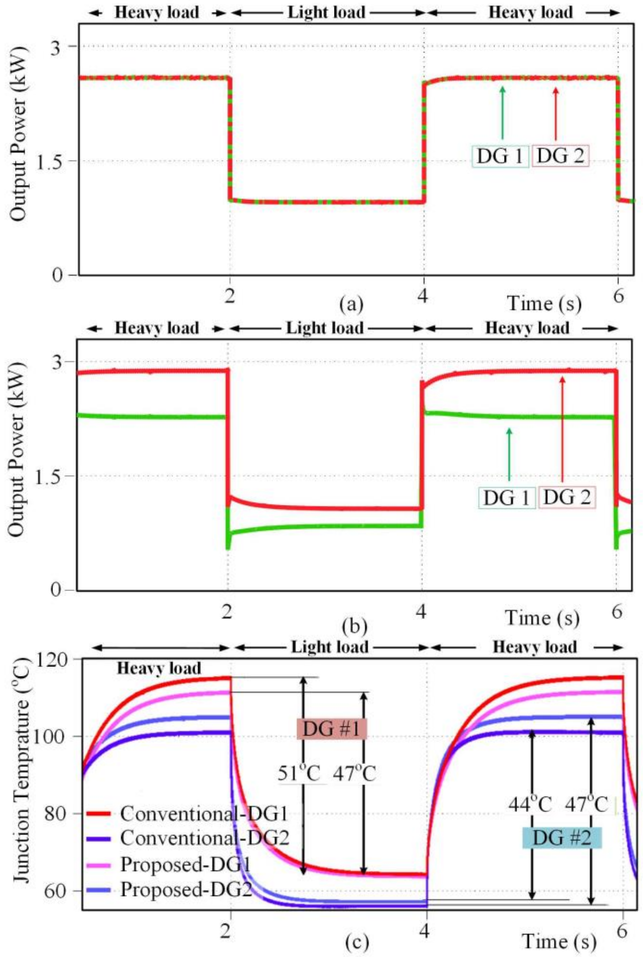
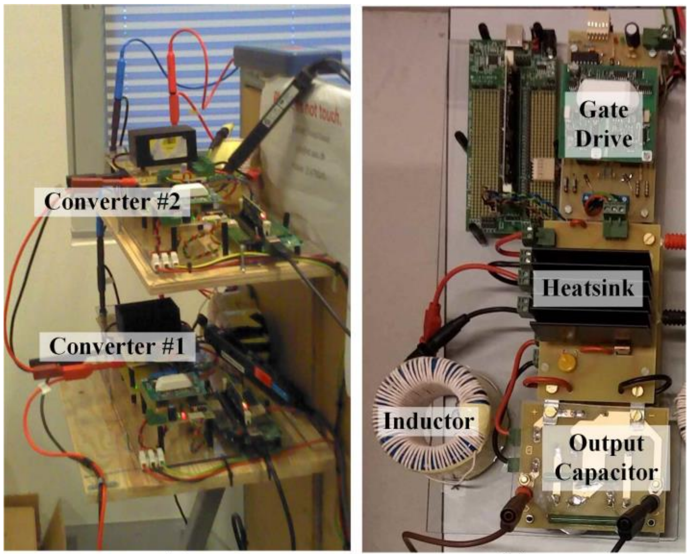
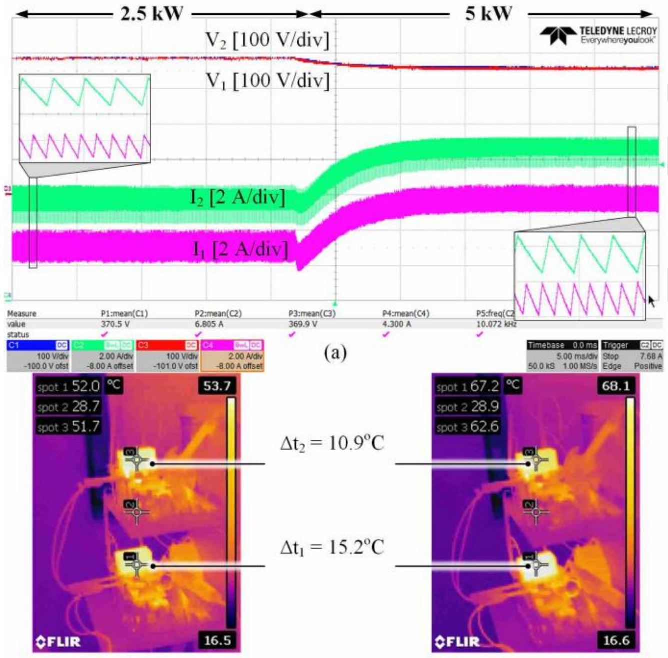


Fig. 4. Simulation results: (a) output power with conventional droop controller – R_{d1} = R_{d2} = 1.5, (b) output power with proposed droop controller – R_{d1} = 1.5 and R_{d2} = 1.1, and (c) junction temperature of converters with conventional and proposed droop approach – light-load (2.5 kW) and heavy-load (5 kW).



(a) (b)

Fig. 5. Photograph of the implemented dc grid including two dc-dc boost converters (a) and boost converter (b).

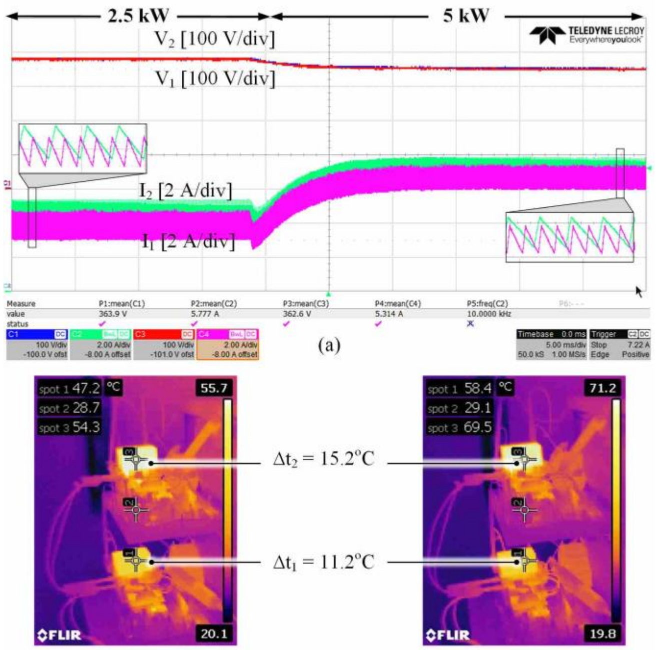


(a)

(b) (c)

Fig. 6. Experimental results: R_{d1} = 1.5 and R_{d2} = 0.9. (a) Output voltage and inductor currents of converters. Temperature of converters' heatsink at (b) light-load (2.5 kW), and (c) heavy-load (5 kW).

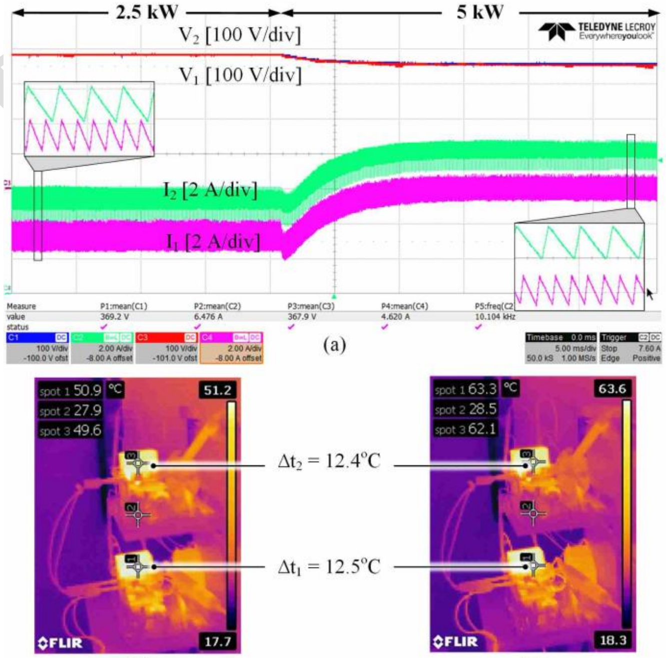
In the next test, the droop gains are set to R_{d1} = 1.5 and R_{d2} = 1.5, and hence the converters are supplying the same portion of the load power as shown in Fig. 7(a). The temperature of the converters' heatsink at light and heavy load is also shown in Fig. 7(b & c), where Δt_1 = 11.2 ºC and Δt_2 = 15.2 ºC. Hence, the temperature stress on the second converter is higher than the first one. Therefore, regarding the life cycle model, supplying the considered load profile consumes more lifetime from the second converter as compared to the first one.



(a)

(b) (c)

Fig. 7. Experimental results: R_{d1} = 1.5 and R_{d2} = 1.5. (a) Output voltage and inductor currents of converters. Temperature of converters' heatsink at (b) light-load (2.5 kW), and (c) heavy-load (5 kW).



(a)

(b) (c)

Fig. 8. Experimental results: R_{d1} = 1.5 and R_{d2} = 1.1. (a) Output voltage and inductor currents of converters. Temperature of converters' heatsink at (b) light-load (2.5 kW), and (c) heavy-load (5 kW).

Finally, setting the droop coefficients equal to R_{d1} = 1.5 and R_{d2} = 1.1, the loading of the converters are shown in Fig. 8(a), and the corresponding heatsink temperatures at light and heavy load are shown in Fig. 8(b & c). As these results indicate, both converters are enduring the same temperature stress Δt_1 = 12.5ºC and Δt_2 = 12.4ºC for the given load profile. Thereby, the consumed lifetime of both converters is the same in which the overall system reliability can be enhanced by selecting appropriate droop gains.

VI. CONCLUSIONS

In this paper, a novel power sharing approach is proposed for the overall system reliability enhancement of dc/dc converters in a dc PEPS. This approach takes into account the lifetime of semiconductors as a much vulnerable component in terms of temperature/power cycling effects on a converter for improving the overall system reliability by thermal management. As a result, the consumed lifetime of converters are equal for the converters and the thermal damages can be appropriately shared among them. Simulation and experimental results demonstrate the effectiveness of the proposed approach.

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